Evaluating Microwave Diathermy Results Using Robotic Arm Guided Temperature Measurement System

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***Abstract*— Microwave diathermy is used for thermal rehabilitation to inhibit the early stages of osteoarthritis (OA). Thermal therapy focusing on the deep joint tissue effectively prevents cartilage degradation. However, our previous experimental results using agar phantoms show that microwave diathermy heat penetration depth is less than 20mm, which is not enough to heat the deep tissue for effective treatment of OA.**

In this study, we evaluated the performance of a microwave diathermy system no different than those used in clinics. To evaluate the system's performance, we compared temperature increase distributions of our experimental results and our simulated results calculated by the finite element method (FEM).

First of all, we developed a method using ultrasound (US) imaging techniques to calculate temperature increase distributions inside the human body. To carry out this new method, we understood that the US imaging probe needed to be precisely positioned in order to compare the ultrasound images taken before and after the heating treatments. Because of this, we developed a robotic arm guided imaging system for our experiments.

Second, we simulated temperature distributions inside the knee using FEM. In order to do this, we utilized a 3D anatomical human knee model reconstructed from MRI images.

Third, we compared and discussed our experimental results and simulation results.

Our findings confirmed that the microwave diathermy system was not able to heat the deep knee tissue. Furthermore, it can be suggested that our robotic arm guided ultrasound system effectively evaluated temperature increase distributions inside the human body during microwave diathermy treatment.

***Index Terms*— Microwave diathermy, Ultrasound imaging, Robotic arm, Temperature increase distributions, Finite Element Method (FEM).**

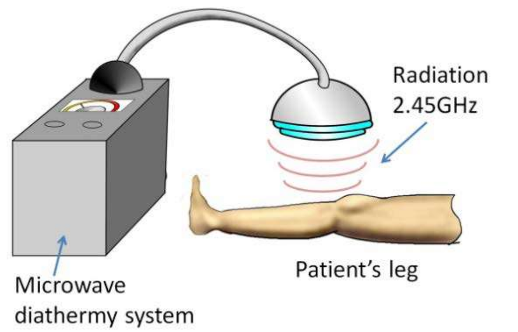

Fig. 1. Illustration of the microwave diathermy treatment setup

I. INTRODUCTION

Microwave diathermy systems are widely used for treating musculoskeletal disorders in clinics. An illustration of this treatment is shown in Fig. 1. This method is one type of thermal rehabilitation to inhibit osteoarthritis (OA) progression in the early stages [1]-[3].

Microwave diathermy systems are typically set at 2.45 GHz. Because of the wavelength, it is not efficient to heat the deep tissue by using this method. In our previous work, we experimented with some agar phantoms using a microwave diathermy system set at clinical conditions [4]-[10]. Our previous findings showed that this heating system was able to effectively heat less than 20 mm deep into the body [9], [10].

In this study, we experimented on the knee of a healthy male subject. To evaluate the heating treatment's effectiveness, we needed to develop a non-invasive temperature distribution calculation system. In other researchers' work, temperature measurement systems using CT or MRI data were developed; however, these methods have a prohibitive cost and take up too much space[11]-[15]. Furthermore, the temperature sensitivity of these methods is around 5°C. To overcome the shortcomings of CT and MRI measurement systems, we developed a new method using ultrasound imaging techniques to calculate temperature increase distributions inside the human body[16]-[18]. We believe our measurement system was easier to use, more economical, and more precise than CT and MRI systems. The basis of this method was already tested in our previous works [18], and we found that this system's algorithm was able to effectively calculate temperature distributions inside the human body.

In our previous study, we had to manually adjust the ultrasound probe's position; however, we noticed that the most important parameters for correct temperature distribution measurement are the precise 3D positioning and angle of the probe. Therefore, in this study, we developed a new non-invasive temperature measurement system guided by a robotic arm, shown in Fig. 2. In our new temperature measurement system, ultrasound images taken before and after heating are input into our in-house image processing software program which then outputs the displacement data.

To evaluate our new ultrasound measurement system, we performed heating experiments using microwave diathermy, and we measured the resulting temperature distribution inside the human subject's knee. We compared these results with the calculated results by FEM (Finite Element Method) using a 3D anatomical human knee model.

II. METHODS

A. Temperature measurement system using ultrasound imaging

It is known that acoustic velocity depends on the temperature of the medium. Ultrasound imaging devices reconstruct images using a specific velocity, so ultrasound images taken before thermotherapy will differ from ultrasound images taken after because of changes in tissue temperature [19]-[22]. We can calculate the temperature distribution inside the human body by the following equations:

$$\Delta T(x) = k_{tissue} \cdot \frac{\partial(\Delta d)}{\partial x} \quad (1)$$

$$k_{tissue} = \frac{1}{\alpha - \beta} \quad (2)$$

Here, T is the tissue temperature, Δd is the displacement between the ultrasound images taken before and after heating, k_{tissue} is the heat coefficient of each tissue, α is the coefficient of thermal expansion of each tissue, and β is the ultrasound speed factor, which changes depending on the tissue temperature. In this study, we calibrated "k_{tissue}" after the experiment.

Figure 3 shows a flow chart of our temperature measurement method using ultrasound images. The basic performance of this proposed method has been evaluated in our previous studies, and we found that it worked effectively. [17], [18].

First, we took an ultrasound image (labeled Img. 1). Next, we carry out the heating treatment. In heating experiments, we heated a human knee with a microwave diathermy system by 100W in 10 minutes, which is the same heating condition in clinics. After that, we took another ultrasound image in the exact same position where Img. 1 was taken (labeled Img. 2).

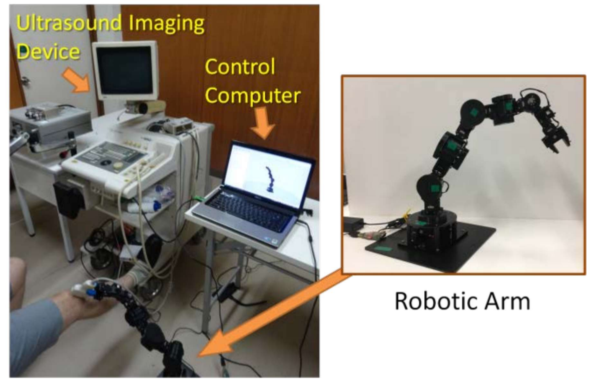

Fig. 2. Robotic arm-guided temperature measurement system.

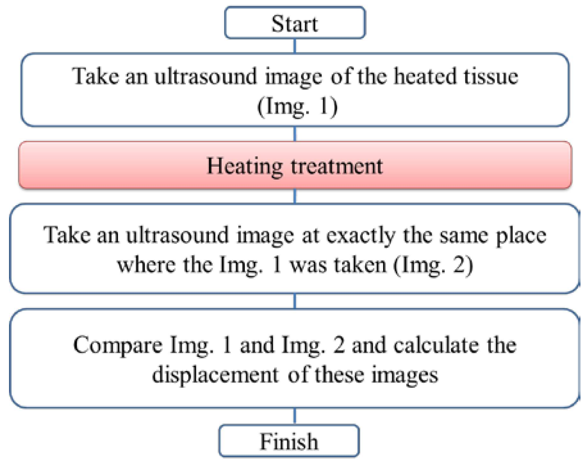

Fig. 3. Flowchart of temperature measurement using ultrasound images.

Fig. 4. Leg brace for assisting in ultrasound imaging.

During this crucial step, the ultrasound imaging probe must be precisely positioned in order to properly compare the images taken before and after the heating treatments. Finally, we calculated the displacement distribution between Img. 1 and Img. 2.

B. Properties of the leg brace and the robotic arm

For this research study, we took ultrasound images of the left knee of one of the co-authors of this study, keeping in mind that the knee joint is difficult to hold in a stable position on its own. Fig. 4 shows a leg brace that was custom-made by a prosthetist for the human subject. With this leg brace, the human subject's leg can be stabilized for taking precise ultrasound images before and after heating.

In this study, we developed robotic arm which guides the ultrasound probe in our measurement system shown in Fig. 5.

It has 7 independent axes, and its maximum payload is 1500g at full reach. This robotic arm can be controlled by the C++ programming language. In this study, we programmed a function which stores the robotic arm's initial 3D position and angle in memory and thus allows it to return to the initial position at any time. Using this function, we are able to take ultrasound images before and after heating as smoothly and actually as possible.

C. FEM calculation model

The FEM calculation model using microwave diathermy is shown in Fig. 6. This anatomical human knee model was reconstructed from MRI images. There are 1,691,945 elements and 287,384 nodes. The microwave frequency radiating from the antenna is set at 2.45GHz. This model is surrounded $1m^3$ of space to be used as the calculation area.

The temperature distribution inside a heated object can be calculated by the following equations, (3)-(8):

$$\nabla^2 E + k^2 E = 0 \quad (3)$$

$$k^2 = \omega^2 \varepsilon \mu \quad (4)$$

$$W_h = \frac{1}{2}\sigma|E^2| \quad (5)$$

$$SAR = \frac{1}{\rho} W_h \quad (6)$$

$$\rho c \frac{\partial T}{\partial t} = \nabla\kappa \cdot \nabla T + \rho \cdot SAR - W_C \quad (7)$$

$$W_C = (F\rho)_{tissue} \cdot (\rho c)_{blood} \cdot (T - T_b) \quad (8)$$

Here, E is the electric field vector, ω the radial frequency, ε the dielectric constant, μ the magnetic permeability, W_h the heat energy generated inside a human body, σ the electrical conductivity, ρ the volume density of tissue, c the specific heat of tissue, κ the thermal conductivity, T the temperature of tissues, t the heating time, Wc the cooling energy by blood flow, and F the blood flow rate of each tissue. Equations (3) and (4) can be solved numerically by FEM [6]-[8]. Using the resulting data of SAR distributions inside a human body, the tissue temperature (T) can be calculated by equation (7). The electrical parameter values at 2.45GHz for each tissue are listed in Table I [23]-[26]. Thermal properties of each tissue are listed in Table II [27]-[31].

III. Results and Discussion

Fig. 7 shows the ultrasound images and estimated temperature increase distribution inside of a human knee joint. In Fig. 7, (a) and (b) show the ultrasound images before and after the heating experiment. Using these ultrasound images, temperature increase distribution shown in Fig. 7(c) was estimated. In this study, we estimated the temperature increase distribution of the deep knee tissue (aiming to the cartilage). From these results, these images of the cartilage and deeper region of the knee showed no differences. However, the hollow bone region showed some differences because of the temperature increase. From this estimated temperature distribution, it was found that the proposed measurement system was effective in estimating the temperature distribution inside the human tissue.

Fig. 5. Developed robotic arm with 3D position memory function.

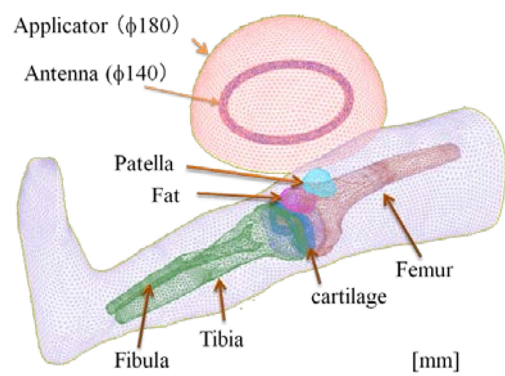

Fig. 6. Finite element model of the microwave diathermy system.

Table I. Electromagnetic properties of tissue at 2.45GHz.

	Electric conductivity [S/m]	Relative permittivity	Density [kg/m^3]
Muscle	1.7388	52.729	1000
Bone	0.39431	11.381	1790
Cartilage	1.7559	38.77	1200
Fat	0.10452	5.2801	900
Air	0.00	1.00	1.165

Table II. Thermal properties of tissue.

Tissue	c [J/kg/K]	κ [W/m/K]	*F* (Blood flow rate) [ml/min/gm]
Muscle	1.7388	52.729	0.027
Bone	2700	0.22	0.1
Cartilage	1.7559	0.35	0.1
Fat	3920	0.24	0.21
Air	1010	0.025	-

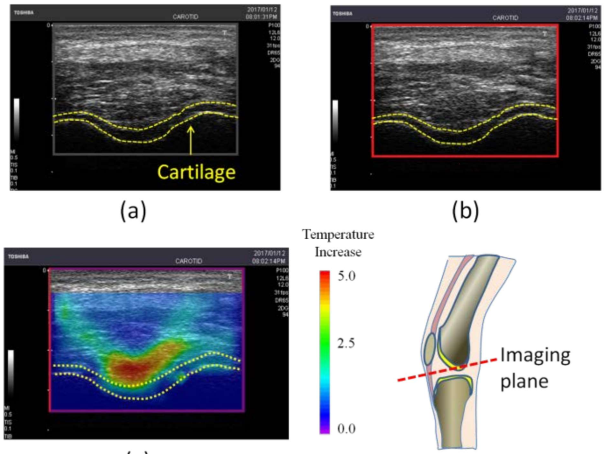

Fig. 7. Ultrasound knee images and calculated temperature distribution.
(a) Before heating, (b) After heating,
(c) Estimated temperature increase distribution

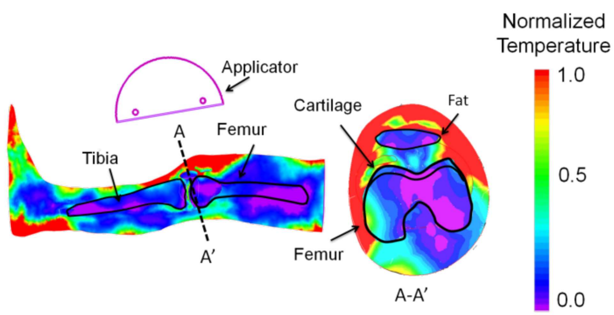

Fig. 8 Simulated temperature distribution by FEM.

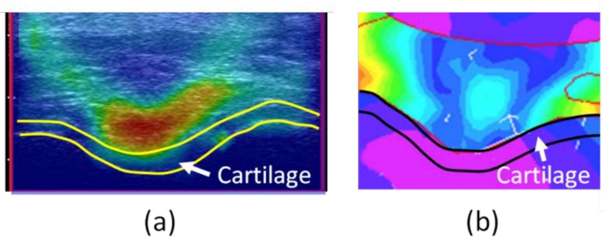

Fig. 9 Enlargement view of temperature increase distributions
(a) Estimated from the ultrasound image, (b) FEM simulated result.

Furthermore, from this experiment it was found that the positioning differences of the probe between before and after the heating was within 0.2 mm by supporting with developed robotic arm.

Fig. 8 shows the normalized temperature distribution calculated by FEM. Here, the normalized Temperature is given by the following equation,

$$\mathrm{T}_N = \frac{(T - T_{\min})}{(T_{\max} - T_{\min})} \qquad (9)$$

where T_N is the normalized temperature, T_{min} is the minimum temperature, T_{max} is the maximum temperature and T is the variable temperature in the human body.

From calculated results, it was found that the most of the electromagnetic heating energy radiated from the antenna was absorbed by the surface of the knee, and it did not reach the cartilage or joint cavity.

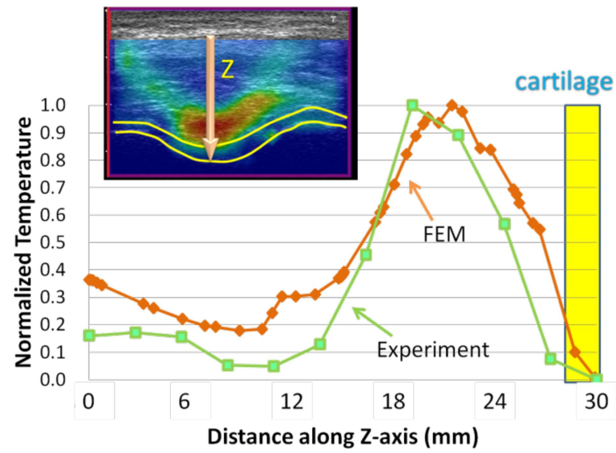

Fig. 10 Normalized temperature distribution along Z-axis (comparing the experimental result and the simulated result)

Fig. 9 shows an enlarged view of both results in the same region of the knee. Both of the distributions showed that the heating energy was concentrated in the hollow bone region and did not reach the cartilage or deep region.

Fig. 10 shows the results of the comparison between the normalized temperature increase profiles inside the knee of the experimental results and FEM calculation results. The maximum temperature in the FEM calculation results was at the depth of 19.2 mm, while the maximum temperature in the proposed experimental results was at the depth of 21.4 mm. These two locations showed only a difference in distance of less than 10%. Furthermore, both results show that, as intended, the inside of the cartilage was not heated.

From these results, we confirmed that the microwave diathermy system could not effectively heat the deep tissue in the knee. Furthermore, we found that by using ultrasound imaging techniques, we were able to calculate the temperature increase distributions inside the human body. And developed system can be able to measure the temperature in 0.5-1.0°C in this situation by using robotic arm. This sensitivity is better than the measurement system using CT or MRI.

IV. Conclusion

In this study, we evaluated the performance of a microwave diathermy system currently used in clinics. To evaluate the system's performance, we compared temperature increase distributions of our experimental results and the calculated results the FEM.

From these results, it can be suggested that our robotic arm guided ultrasound system effectively evaluated temperature increase distributions inside the human body during microwave diathermy treatment. Furthermore, we confirmed that the microwave diathermy system was not able to heat the deep tissue region of the knee.

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